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Article

Physico-chemical characterization of a low cost biosorbent for efficient sequestration of heavy metals

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Abstract: Heavy metal pollution from industrial effluents poses significant environmental and public health challenges, particularly in aquatic ecosystems. Traditional wastewater treatment methods, are effective but often expensive, labor-intensive, and generate hazardous waste. Biosorption, using biological materials, presents a cost-effective and environment friendly alternative for heavy metal removal. The present study investigates the potential of *Madhuca indica* oil cake, a by-product of oil extraction can be used as a biosorbent for heavy metal sequestration. The oil cake was characterized by its physicochemical properties, including specific gravity (1.298 g/cm^3), bulk density (0.66184 kg/m^3), moisture content (11.34%), and dry matter content (88.66%). These properties suggest the oil cake is dense, nutrient-rich, and easy to handle and store. Fourier Transform Infrared (FTIR) spectroscopy was used to analyze the functional groups in the oil cake before and after drying at 105 °C. The results showed minimal changes in the chemical composition, with a slight shift in peak intensities indicating concentration effects due to drying. This stability is crucial for applications requiring intact bioactive compounds. The study highlights the versatility of *Madhuca indica* oil cake for multiple uses, including animal feed, fertilizer, and biomass for bioenergy. Furthermore, its potential as a biosorbent for heavy metal removal underscores its promise for environmental remediation. The study concludes that further research could optimize the utilization of *Madhuca indica* oil cake in agriculture and pollution control, contributing to sustainable environmental management.

Keywords: oil cake; *Madhuca indica*; biosorption; heavy metal; environment pollution; toxic

1. Introduction

Heavy metal pollution in aquatic ecosystems and industrial effluents is a major environmental problem. Heavy metals are toxic and non-biodegradable, and they persist and accumulate in the food chain. This makes heavy metal pollution a significant public health and environmental concern [1]. As a consequence of this, heavy metals constitute a significant environmental concern. One of the most major contributors to heavy metal pollution is electroplating, which is responsible for the release of metals such as chromium, zinc, nickel, and cadmium into the environment [2]. The mining industry, the generation of electricity, agriculture, and metallurgy are other significant contributors to the pollution caused by heavy metals. Industrial effluents include high amounts of these metals, which represent significant dangers to both surface water and groundwater. These metals contribute to global warming. Among the possible consequences of these metals are their toxicity to aquatic life, their pollution of drinking water, and their bioaccumulation in the food chain, which may result in serious health issues such as neurological diseases and lung cancer. Given that multiple heavy metal ions are known to cause cancer and mutations, it is of the highest significance to treat wastewater before it is discharged into the environment. This is because of the fact that heavy metal ions are known to cause cancer. The concentration of heavy metals in effluents and drinking water is subject to tight regulations that have been set by regulatory bodies such as the Environmental Protection Agency (EPA) of the United States of America. These restrictions protect the public from exposure to harmful levels of heavy metals. To provide one example, the concentration of zinc should not be more than 5 mg/L [3]. Compliance with these criteria, in combination with the implementation of advanced wastewater treatment systems, is very necessary in order to lessen the dangers that heavy metal pollution presents to both the health of humans and the health of the environment.

Chemical precipitation, ion exchange, electrochemical treatment, membrane technology, and adsorption on activated carbon are some of the several ways that have been developed for the purpose of treating hazardous metal effluents [4]. Despite the fact that these techniques are capable of properly removing heavy metals, they come with a number of major downsides, including high prices, labor intensity, and often being prohibitively expensive. Furthermore, they do not promote the recycling of metal ions and produce concentrated hazardous wastes, which results in difficulties with disposal and a reduction in efficacy when metal concentrations are increased. For instance, chemical precipitation generates a substantial quantity of sludge that is cumbersome to dispose of, ion exchange resins are costly and less effective at high metal concentrations, electrochemical treatments have high energy demands and maintenance requirements, membrane technologies are plagued by problems such as fouling and high operational costs, and activated carbon, despite its widespread application, loses its effectiveness over time and presents difficulties in terms of disposal. In light of these constraints, there is an increasing desire for alternative wastewater treatment procedures that are more cost-effective, sustainable, and effective over a wide range of metal concentrations. Emerging methods include phytoremediation, which makes use of plants to absorb and detoxify metals, but takes more time and space than biosorption does. Biosorption, which makes use of natural materials such as agricultural waste and microbial biomass, is an alternative that is both inexpensive and has the ability to be reused. Nanotechnology also shows promise, with nanomaterials such as metal oxides and carbon-based nanoparticles demonstrating great efficiency in the removal of metals. However, there are still issues to be faced in the use and disposal of nanomaterials using large-scale applications. By combining electrocoagulation with renewable energy sources like solar power, it is possible to make the process more cost-effective and sustainable. Geopolymer technology provides a method to immobilize heavy metals in a stable matrix, which may make it possible to reuse water and dispose of trash in a secure manner. When it comes to tackling the limits of traditional treatments, it is necessary to develop and apply these novel solutions. This will ensure that wastewater treatment is both economically feasible and ecologically responsible.

Due to the limits of traditional techniques in terms of cost, environmental effect, and efficiency, biotechnological approaches for regulating and eliminating metal pollution have recently attracted substantial interest. This is especially owing to the fact that conventional methods also have limitations. According to [5] biosorption has emerged as a solution that shows a great deal of promise among these several ways. For the purpose of removing hazardous heavy metals from wastewater, biosorption makes use of natural materials that are of biological origin. These resources include bacteria, fungus, algae, and waste from agricultural production. This method is efficient in terms of cost since it makes use of low-priced, easily accessible raw materials and requires just a little amount of energy to maintain its operation. In addition to this, it is ecologically benign since it produces a little amount of toxic sludge and prevents the release of dangerous chemicals into the environment. The ease of use of biosorption, in conjunction with its high efficacy in removing metals from solutions that are dilute, gives it a treatment option that is both accessible and effective, especially in situations where conventional approaches may fail. Biosorption, on the other hand, lacks the need for the addition of any extra chemicals or nutrients, which further mitigates the complexity and expenses of operations. The capacity to regenerate and reuse the biosorbent materials is one of the most significant benefits of biosorption. This not only contributes to the enhancement of sustainability but also makes it possible to recover precious metals from waste streams. Although these benefits are there, there are still problems that must be overcome, such as the requirement for efficient regeneration processes and the unpredictability in the performance of biosorbents. Nevertheless, continuing research, which includes developments in genetic engineering, shows promise for overcoming these problems and further enhancing biosorption for uses on an industrial scale. Biosorption has the potential to become a widely accepted and sustainable solution for controlling heavy metal pollution, contributing to both the preservation of the environment and the recovery of resources. This potential is expected to continue to grow as these advancements continue [6]. Plant materials and their byproducts have been extensively studied for metal removal from wastewater. In the context of biodiesel production, especially in countries like India, non-edible oil sources like *Madhuca indica* Linn are being explored as alternatives to fossil fuels. The oil cake, a byproduct of biodiesel production from *Madhuca indica* Linn, is investigated in this study for its potential as a biosorbent for heavy metal sequestration. The physicochemical properties of *Madhuca indica* Linn oil cake were analyzed to assess its suitability for this purpose.

2. Materials and methods

2.1. Collection and preparation of biosorbent

The process of extracting oil from *Madhuca indica* Linn seeds produces the by-product known as *Madhuca indica* oil cake. This residual material, after extraction, has significant applications, including environmental remediation, as demonstrated in the present study. After oil extraction, the oil cake was shade dried to remove excess moisture, enhancing its stability and shelf life. This step makes the oil cake more suitable for further applications. To achieve a consistent and manageable particle size, the dried oil cake is sieved through a mesh, typically 40–60 mesh. This sieving process ensures uniformity and optimal particle size for subsequent analysis and applications.

The sieved *Madhuca indica* oil cake is then subjected to a series of analyses, including physico-chemical parameters such as specific gravity, bulk density, moisture content, and dry matter percentage. These parameters provide essential insights into the characteristics of the oil cake, influencing its suitability for adsorption purposes. Additionally, Fourier Transform Infrared (FTIR) analysis is conducted to examine the functional groups present in the oil cake, revealing its chemical composition and potential interactions with heavy metal ions during the adsorption process.

2.2. Physicochemical properties of biosorbent

Specific gravity and bulk density are crucial physicochemical properties that offer insights into the structural and density characteristics of a biosorbent. These properties are particularly relevant when evaluating materials for their adsorption capabilities, such as in the removal of heavy metals from aqueous solutions [7]. Specific gravity and bulk density were determined using a 25 mL specific gravity bottle, following established Equations (1) and (2).

$$specific\ gravity = \frac{\text{weight of the sample}}{\text{weight of equal volume of water}} = \frac{(W2 - W1)}{[(W4 - W1) - (W3 - W2)]} \quad (1)$$

$$Bulk\ density = \frac{weight\ of\ the\ sample}{volume} \quad (2)$$

These physicochemical properties provide valuable information about the biosorbent's structure, porosity, and density, which are crucial considerations for its effectiveness in adsorption applications, such as heavy metal removal from aqueous solutions.

2.3. Determination of Moister and dry matter

Dry matter content was assessed by placing a measured quantity of the sample in a vacuum oven at 105 °C for 4 h. The resulting dry weight of the sample was measured using an electronic balance. Subsequently, the percentage of moisture and dry matter was calculated using the following Equations (3) and (4).

$$\text{Moister}(\%) = \frac{\text{Initial weight} - \text{final weight}}{weight\ of\ the\ sample} \quad (3)$$

$$\text{Dry matter}(\%) = \frac{\text{weight of oven dried sample}}{weight\ of\ the\ sample} \quad (4)$$

2.4. Fourier Transform Infrared (FTIR) spectroscopy analysis

FTIR spectra were recorded on a Perkin Elmer Spectrum One equipped with an ATR-FTIR unit. A few milligrams of sub-fraction of the sample were placed in the head of ATR. The spectra were obtained with a resolution of 4 cm^{-1} and 16 co-addition scans in a wavelength range of 450–4000 cm^{-1}. The spectra were collected and analyzed using Spectrum software (Perkin Elmer). The FTIR spectra of the sample were recorded both before and after heating in a vacuum oven at 105 °C for 4 h using Fourier Transform Infrared Spectroscopy (FTIR). This analysis aimed to elucidate changes in the surface composition and molecular structure of the sample due to the heating process [8].

3. Result and discussion

The physicochemical properties *Madhuca indica* oil cake various are showed in table (**Table 1**).

Table 1. Physicochemical properties Madhuca indica oil cake.

Properties	**Oil cake**
Specific Gravity (g/cm^3)	1.298
Bulk Density (kg/m^3)	0.66184
Moister (%)	11.34
Dry Matter (%)	88.66

3.1. Specific gravity

The oil cake made from *Madhuca indica* has a specific gravity of 1.298, which shows that it is much denser than water. The fact that the oil cake has a relatively high density indicates that it contains a considerable quantity of solid material in relation to its own volume. This indicates that the oil cake will sink in water, which may be significant for specific processing or separation processes. In other words, this describes the practical implications of the situation. According to Ramadan et al. (2015), this feature also suggests that the material is highly compact, which might be helpful for transportation and storage since it would take less space compared to materials that are less dense.

3.2. Bulk density

The data reveal that the bulk density of *Madhuca indica* oil cake was found to be 0.66184 kg/m^3, which indicates that the oil cake has a comparatively low mass per unit volume when the material is evaluated in its bulk form. This means that the oil cake has a relatively low mass per unit volume. The fact that the oil cake has a lower bulk density is evidence that it is both lightweight and porous. This is because the oil cake has a lower bulk density. The low bulk density of the material makes it relatively easy to mix it with other components of feed or soil when it comes to agricultural applications, such as the use of the material in animal feed or as an amendment to the soil. Other agricultural applications include the use of the material in animal feed. It is also conceivable for it to imply great aeration capabilities when it is used as a soil amendment, which has the capacity to increase soil structure and root penetration [9]. This is supported by the fact that it has the potential to improve soil structure.

3.3. Moisture content

There is a moderate quantity of water present in *Madhuca indica* oil cake, as shown by the moisture content of 11.34%, which was found in the oil cake. The moisture level is often low, which is beneficial for storage and shelf life since it allows for longer shelf life. Specifically, this is due to the fact that a reduced moisture content reduces the risk of microbial formation and degradation, which is beneficial for both storage and shelf life. On the other hand, in order to prevent the material from becoming too brittle and to prevent it from losing its degree of flexibility, it is necessary to have a certain quantity of moisture present. Additionally, the presence of moisture has the effect of making the process of processing the oil cake easier. This is due to the fact that material that is highly dry may be more challenging to deal with and may increase the amount of particles [10].

3.4. Dry matter content

Madhuca indica oil cake recorded to have dry matter of about 88.66%. It is clear from the high dry matter percentage that the oil cake is rich in organic matter and nutrients, which makes it a very valuable resource that may be used in a variety of applications. Having a high dry matter content in the context of animal feed indicates that the oil cake is capable of delivering a significant quantity of nutrients to the animal without contributing an excessive amount of moisture to the diet. The high dry matter content indicates that there is a concentration of organic matter and potential soil nutrients [11]. This is in reference to the usage of the material as a fertilizer.

3.5. Fourier Transform Infrared (FTIR) spectroscopy analysis

Figures 1 and **2** shows the spectra of fresh oil cake and dried oil cake of *Madhuca indica* respectively.

Fourier Transform Infrared (FTIR) spectroscopy is a powerful analytical tool used to identify and analyze organic, polymeric, and sometimes inorganic materials. It operates by measuring the absorption of infrared radiation at various wavelengths, producing a spectrum that reveals vibrational frequencies of chemical bonds within the sample. In the original sample's FTIR spectrum, the highest peak observed at 1020.16 cm^{-1} likely corresponds to specific functional groups or chemical bonds present in the *Madhuca indica* oil cake. This peak's intensity and position provide insights into the molecular structure of the original sample. Following drying in a vacuum oven at 105 °C for 4 h, the highest peak in the FTIR spectrum of the dried sample shifts slightly to 1017.45 cm^{-1}. This minor shift suggests minimal alterations in the sample's molecular environment due to the removal of water and volatiles during drying, influencing the vibrational frequencies of the functional groups. No new peaks emerged in the spectrum of the dried sample, indicating that the drying process did not introduce new chemical species or induce significant chemical transformations [12]. However, increases in peak intensities were noted, indicating a concentration effect where the drying process enhanced the detectability of existing chemical bonds or functional groups.

These findings affirm that the drying process primarily concentrates the organic constituents of the *Madhuca indica* oil cake without fundamentally altering its chemical composition. This stability is crucial for applications requiring intact bioactive compounds, such as agricultural uses and bioenergy production. The observed increase in peak intensities further suggests enhanced efficacy in these applications due to the concentrated bioactive components within the dried oil cake.

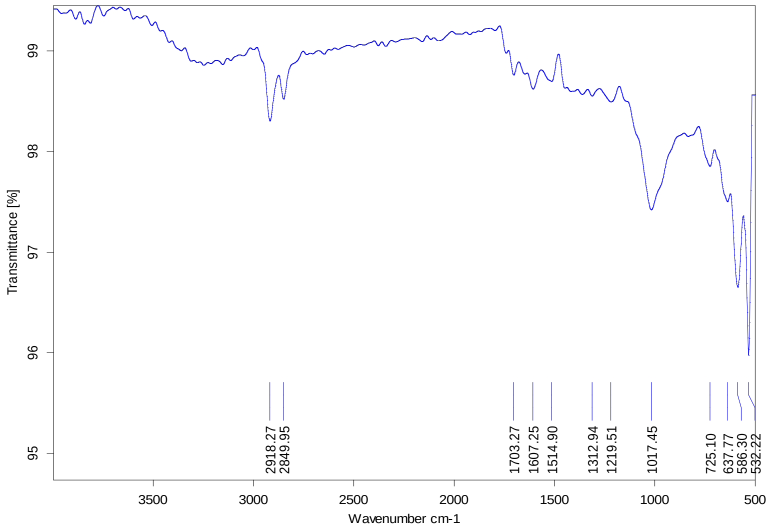

Figure 1. FTIR spectrum of fresh *Madhuca indica* oil cake.

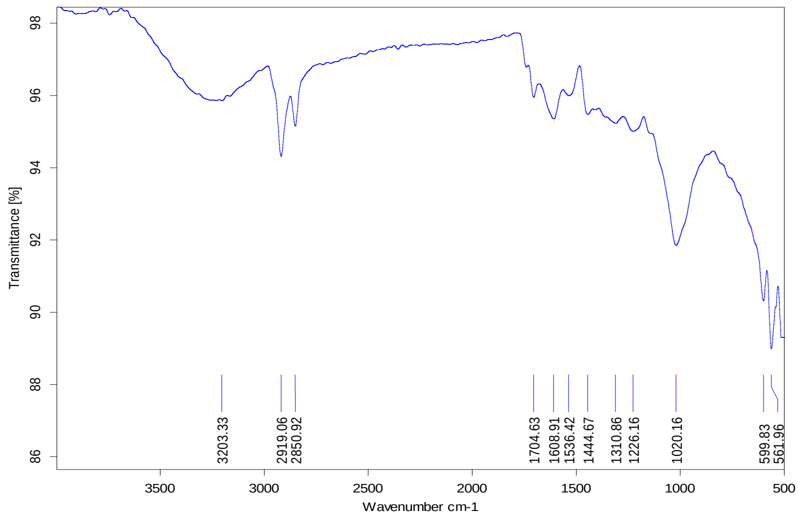

Figure 2. FTIR spectrum of oven dried *Madhuca indica* oil cake.

3.6. Other applications of *Madhuca indica* oil cake

Because it has a high dry matter concentration and a moderate moisture level, oil cake is an excellent choice for inclusion in animal feed ingredients. Producing a high-protein supplement for cattle may be accomplished by either grinding it into a powder or pelletizing it [13]. The specific gravity and bulk density of the feed suggest that it may be readily combined with other feed components without substantially affecting the total volume or weight of the feed. This is consistent with the findings of the study. The fact that *Madhuca indica* oil cake has a high dry matter content indicates that it contains a significant amount of organic material, which is good to the health of the soil. The structure of the soil can be improved, the nutrient content can be increased, and plant development can be supported when it is applied as a fertilizer or an amendment to the soil. According to [14], the low bulk density of this material may also help to aerate the soil, which is advantageous for the formation of roots from the plant. Because of the significant amount of solids that it contains, the oil cake has the potential to be used as a source of biomass for the generation of bioenergy. According to [15], the specific gravity and bulk density are two factors that should be considered while evaluating the effectiveness of transportation and processing strategies in bioenergy plants.

As a consequence of the physicochemical characteristics that it has, *Madhuca indica* oil cake seems to be relatively easy to store and maintain as stated by [16]. The low moisture content of this material makes it less likely to be contaminated by microbes [17]. Additionally, the density features of this material make it easier to transport and store in large numbers. Both of these characteristics contribute to decreased likelihood of contamination.

4. Conclusion

The physicochemical properties of *Madhuca indica* oil cake highlight its versatility and value in various applications. Its high density and dry matter content make it a nutrient-rich material suitable for animal feed and fertilizer, while its manageable moisture content and bulk density facilitate easy handling and storage. FTIR analysis indicates that drying leads to minor shifts in peak positions and increased peak intensities without introducing new chemical species. This suggests the drying process primarily affects the oil cake's physical state, concentrating its constituents without altering its chemical composition. These properties ensure the quality and consistency of the oil cake in various uses. Furthermore, the preliminary study showed that the oil cake could be a potential biosorbent for heavy metal sequestration, indicating its promise for environmental remediation. These findings suggest further research and development could enhance the utilization of *Madhuca indica* oil cake in agriculture and environmental management.

Conflict of interest: The author declares no conflict of interest.

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